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Particle Densities in Heavy Ion Collisions at High Energy and the Dual String Model

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Abstract

We analyse recent results on charged particle pseudo-rapidity densities from RHIC in the framework of the Dual String Model, in particular when including string fusion. The model, in a simple way, agrees with all the existing data and is consistent with the presence of the percolation transition to the Quark-Gluon Plasma already at the CERN-SPS.

Recent results on charged particle pseudo-rapidity densities in central Au+Au collisions, at $\sqrt{s} = 56$ and $\sqrt{s} = 130$ AGeV, presented by the PHOBOS Collaboration, at RHIC, [1], give very interesting information that may help to clarify the way the expected Quark-Gluon Plasma (QGP) is approached as the energy increases. Those data also allow to select among different models of particle production. As in this experiment the charged particle densities and the average number of participating nucleons are simultaneously measured, that provides additional strong constraints to models.

As nuclei are made up of nucleons, it is natural to start by building nucleus-nucleus collisions as resulting from superposition of *nucleon-nucleon* collisions, in the way it is done in the Glauber model approach and generalisations of it. In one (low energy) limit the nucleons are seen as structureless and emit particles only in their first collision: this

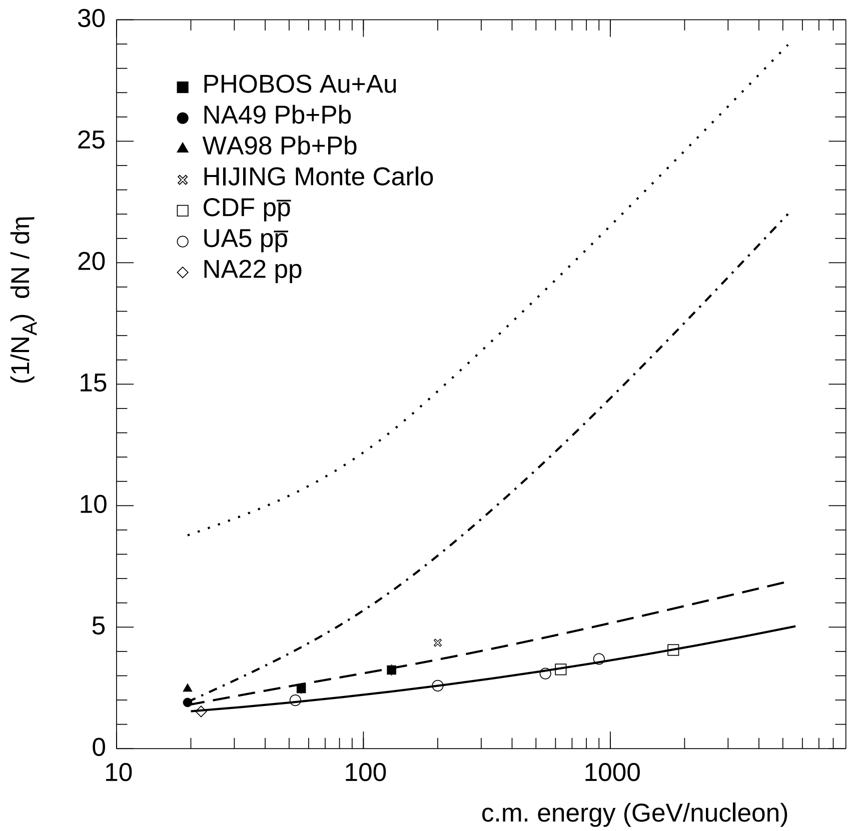

Figure 1: Pseudo-rapidity density normalised per participant pair as a function of c.m. energy. The lines give predictions for the wounded nucleon model Eq. (1) (solid line), the pure multicollision approach Eq. (2) (dotted line), and the Dual String Model, without fusion Eq. (7) (dash-dotted line) and with fusion Eq. (14) (dashed line). AA points are taken from [1, 20, 19], pp and $p\bar{p}$ from [5, 6, 7, 8]

is the wounded nucleon model [2]. The prediction for particle density, when N_A nucleons from each one of the nuclei in a AA collision participate, is

$$\left.\frac{dN}{dy}\right|_{N_A N_A} = \left.\frac{dN}{dy}\right|_{pp} N_A, \tag{1}$$

where dN/dy is the particle rapidity (or pseudo-rapidity) density (for $N_A N_A$ and nucleon-nucleon collisions). If the nucleon is seen as made up of quarks and gluons, with a growing number of participating sea quarks and gluons as the energy increases, one anticipates dominance of multi-collision processes [3] and the relation

$$\left.\frac{dN}{dy}\right|_{N_A N_A} = \left.\frac{dN}{dy}\right|_{pp} \nu_{N_A}, \tag{2}$$

to hold, where ν_{N_A} is the number of nucleon-nucleon collisions when N_A nucleons participate. Elementary multi-scattering arguments [4] give

$$\nu_{N_A} = N_A^{4/3} \tag{3}$$

In Fig. 1, together with the PHOBOS data, we have presented the quantity $\frac{1}{N_A} \left.\frac{dN}{dy}\right|_{N_A N_A}$ as function of the c.m. energy $\sqrt{s}$ for the bounds (1)—solid line—and (2) with (3) —dotted

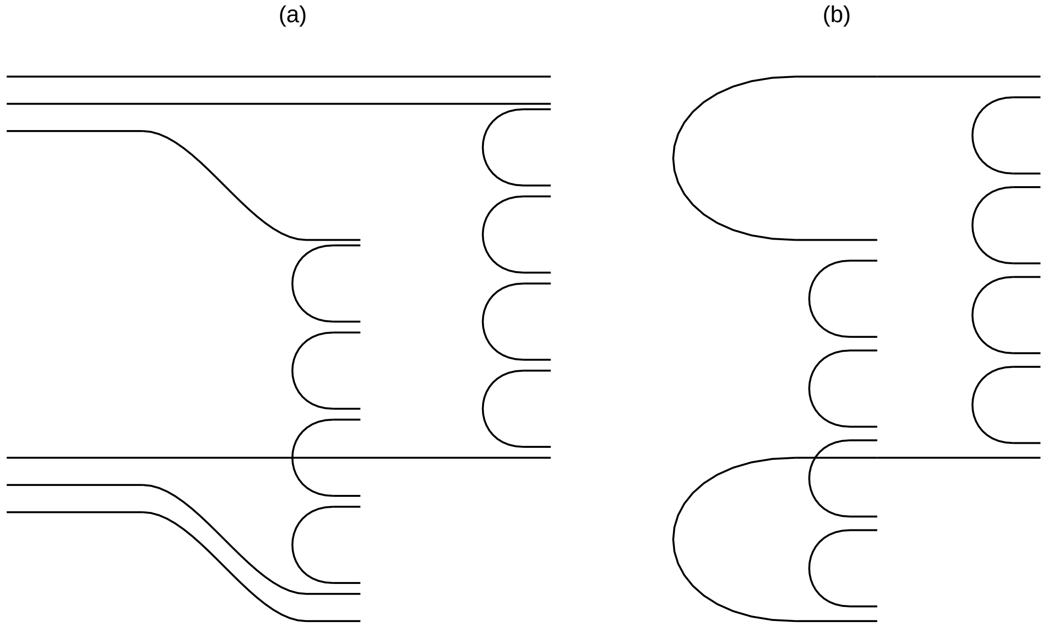

Figure 2: Two strings are produced by each collisions of valence partons (a) and sea partons (b). Notice how the nucleon is broken up in (a), so that further interactions are of the type illustrated by (b). See the text for further discussion.

line. We used for $dN/dy|_{pp}$ the parametrisation $0.957 + 0.0458\ln(\sqrt{s}) + 0.0494\ln^2(\sqrt{s})$, with $\sqrt{s}$ in GeV, which fits data from pp and $p\bar{p}$ non-single-diffractive collisions for c.m. energies $\sqrt{s} \geq 22$ GeV. The parametrisation used in [1, 8] could not be used here because it does not fit NA22 data.

In the Dual String Model (DSM), i.e., the Dual Parton Model [9] with the inclusion of strings [10], the limits referred to above appear in a natural way. The valence quarks of the nucleon produce particles, via strings, only once —this is the wounded nucleon model case— and production is proportional to the number N_A of participant nucleons (Fig 2a). As the energy and N_A increase the role of sea quarks and gluons increases, they interact and produce, again via strings, particles, and the number of collisions ν becomes the relevant parameter (Fig 2b).

One should notice that the diagram of Fig. 2b may be interpreted as multiple inelastic scattering, either internally within a given nucleon-nucleon collision or externally involving interactions with different nucleons. On the other hand, this diagram may appear repeated several times.

Following [4], and taking into account the basic diagrams of Fig.s 2a and 2b, we now write an expression for the particle pseudo-rapidity density,

$$\left.\frac{dN}{dy}\right|_{N_A N_A} = N_A\left[2 + (2k-1)\alpha\right]h + (\nu_{N_A} - N_A)2k\alpha h, \tag{4}$$

where h is the height of the valence-valence rapidity plateau, α is the relative weight of the sea-sea (including gluons) plateau and k is the average number of string pairs per collision. The diagrams of Fig.s 2a and 2b correspond to $k = 1$. However, as we mentioned above,

the diagram of Fig. 2b can be iterated with $k \geq 1$ being, in general, a function of energy. The number of nucleon-nucleon collisions is, of course,

$$N_A + (\nu_{N_A} - N_A) = \nu_{N_A}, \tag{5}$$

and the number N_s of strings is

$$N_s = N_A\,[2 + 2(k-1)] + (\nu_{N_A} - N_A)2k = 2k\nu_{N_A}. \tag{6}$$

The first term on the right-hand side of Eq. (4) is just a sum over nucleon-nucleon scattering contributions (including internal parton multiple scattering) and we can thus write

$$\left.\frac{dN}{dy}\right|_{N_A N_A} = \left.\frac{dN}{dy}\right|_{pp} N_A + (\nu_{N_A} - N_A)2k\alpha h, \tag{7}$$

with

$$\left.\frac{dN}{dy}\right|_{pp} = [2 + 2(k-1)\alpha]\,h. \tag{8}$$

If external multiple scattering is absent, by putting $\nu_{N_A} = N_A$, one obtains the wounded nucleon model limit, Eq. (1). If multiple scattering dominates, $k \gg 1$, we obtain the limit of Eq. (2).

In order to make more transparent the comparison with data, we shall rewrite Eq. (7), by using Eq. (8) and Eq. (3), in the form

$$\frac{1}{N_A}\left.\frac{dN}{dy}\right|_{N_A N_A} = \left.\frac{dN}{dy}\right|_{pp} N_A^{1/3} - (N_A^{1/3} - 1)2(1-\alpha)h. \tag{9}$$

We show the result of this model in Fig. 1 (dash-dotted line). From comparison of Eq. (8) with pp data at low energy, $k \simeq 1$, one obtains $h \simeq 0.75$. The parameter α in Eq. (9) was put equal to 0.05.

In the Dual String Model the strings interact, the simplest interaction being fusion due to overlap in the transverse plane [10]. This is the mechanism that leads to percolation and to the Quark-Gluon Plasma formation [11, 12, 13]. When strings fuse, the strength of the colour field is reduced in comparison with the colour field generated by the same number of independent strings. This is essentially due to the random sum of colour vectors [14]: $Q_n^2 = \sum_{i=1}^{n} Q_i^2$ and $Q_n = \sqrt{n}Q$ if all the n strings are of the same type.

Introducing the dimensionless transverse density percolation parameter η,

$$\eta \equiv \frac{r_s^2 N_s}{R_{N_A}^2}, \tag{10}$$

where r_s is the string transverse radius (we shall take $r_s = 0.2$ fm, see [11, 15]), R_{N_A} the radius of the interaction area ($R_{N_A} \simeq 1.14 N_A^{1/3}$) and N_s the number of strings, the effective reduction factor in particle production is [16],

$$F(\eta) = \sqrt{\frac{1 - e^{-\eta}}{\eta}}. \tag{11}$$

As $\eta \to 0$, $F(\eta) \to 1$ (no fusion) and as $\eta \to \infty$, $F(\eta) \to 1/\sqrt{\eta} \approx 1/\sqrt{N_s}$ (all the strings fuse).

We can consider the parameter η in two situations. In nucleon-nucleon internal interactions, and then

$$\eta_{pp} \equiv \frac{r_s^2}{R_{pp}^2}[2 + (2k - 1)] = \frac{r_s^2}{R_{pp}^2} 2k. \tag{12}$$

At present energies η_{pp} is negligible, $\eta_{pp} \approx 10^{-2} \div 10^{-1}$. But we can also consider η in external interactions, with

$$\eta_{N_A N_A} = \frac{r_s^2}{R_{N_A}^2} 2k(\nu_{N_A} - N_A) \simeq \left(\frac{r_s}{1.14}\right)^2 2k(N_A^{1/3} - 1)N_A^{1/3}. \tag{13}$$

For $N_A \approx 10^2$, as in [1], $\eta_{N_A N_A} > 10\eta_{pp}$ and we shall then only consider $\eta_{N_A N_A}$.

Eq. (4) with string fusion becomes

$$\begin{aligned} \frac{1}{N_A} \left.\frac{dN}{dy}\right|_{N_A N_A} &= \left.\frac{dN}{dy}\right|_{pp} \left[1 - F(\eta_{N_A N_A})\right] \\ &+ F(\eta_{N_A N_A}) \left[\left.\frac{dN}{dy}\right|_{pp} N_A^{1/3} - (N_A^{1/3} - 1)2(1 - \alpha)h \right]. \end{aligned} \tag{14}$$

In Fig. 1 we have also shown the prediction of the DSM with string fusion (dashed line) again with $h = 0.75$ and $\alpha = 0.05$. The deviation from the wounded nucleon model limit becomes weaker and the agreement with PHOBOS data is quite satisfactory.

We would like now to make a few comments:

1. The predictions for particle densities in central Pb+Pb collisions of the DSM without fusion and of the DSM with fusion are very different at $\sqrt{s} = 200$ AGeV (RHIC) and at $\sqrt{s} = 5.5$ ATeV (LHC) as can be seen in the following table, showing the average pseudo-rapidity density in the interval $[-1, 1]$:

c.m. energy	200 AGeV	5.5 ATeV
without fusion	1500	4400
with fusion	700	1400

2. The models considered here are essentially soft models. The parameters of the elementary collision densities, h and α, were assumed constant, all the energy dependence being attributed to the parameter k, the average number of string pairs per elementary collision. If h and α are allowed to grow with energy, as a result, for instance, of semi-hard effects, the parameter k may then have a slower increase than the one obtained here.

3. The value found for α, $\alpha \simeq 0.05$, means that the height of the sea-sea plateau is much smaller than the height of the valence-valence plateau. By noticing that for valence-valence collisions the two strings stretch all over forward/backward rapidity without much overlap, while for sea-sea collisions the two strings do overlap, the value found for α means

$$\left.\frac{dN}{dy}\right|_{\text{sea-sea}} \simeq 0.1 \left.\frac{dN}{dy}\right|_{\text{val-val}}. \tag{15}$$

4. In our Dual String Model with fusion, the parameter $\eta_{N_A N_A}$ at the CERN-SPS has the value $\eta_{N_A N_A} \approx 1.8$, larger than the critical density ($\eta_c \approx 1.12 \div 1.17$) which means that percolation transition is already taking place at $\sqrt{s} = 20$ AGeV, even allowing for non-uniform matter distribution in the nucleus ($\eta_c \approx 1.5$) [17]; this result is valid even with $k = 1$. The observed anomalous J/ψ suppression [18] may then be a signature of the percolation transition to the Quark-Gluon Plasma [13].

After the submission of this paper, we became aware of two papers on the same subject [19, 20].

1. From the paper of Wang and Gyulassy [19] we realised that the HIJING point at 200 AGeV in Ref. [1] was 20% too high. This point was corrected in our figure.

2. In the WA98 Collaboration paper on scaling of particle and transverse energy production [20], results on dN/dy were presented in Pb+Pb collisions at 158 A GeV. This point was included in Fig. 1 but not taken into account in the calculations. It somewhat disagrees with the NA49 point presented in [1].

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